Army Research Laboratory

# Interoperation of the Wireless Emulation Laboratory (WEL) and the System-of-Systems Survivability Simulation (S4): 2011 Year-End Status of the Director's Strategic Initiative and Results

**by Jeffrey A. Smith, Brian Rivera, and Rommie L. Hardy**

**ARL-TR-5867** **January 2012**

## NOTICES

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White Sands Missile Range, NM 88005

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# Interoperation of the Wireless Emulation Laboratory (WEL) and the System-of-Systems Survivability Simulation (S4): 2011 Year-End Status of the Director's Strategic Initiative and Results

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**14. ABSTRACT**

The U.S. Department of Defense (DoD) is pursuing an end-to-end, seamless network-centric enterprise communications infrastructure. Evaluating this network is essential to guiding requirements, design, and procurement activities. However, the DoD currently lacks the capability to analyze the complex networked interactions between Soldiers and equipment. The U.S. Army Research Laboratory (ARL) has made significant investments developing a variety of modeling and analysis capabilities to analyze the impact of technology solutions on Soldiers. ARL researchers need a suite of tools allowing the System-of-Systems Analysis (SoSA) of technology impact on mission performance.

ARL's Computational and Information Sciences Directorate (CISD) has developed the Wireless Emulation Laboratory (WEL) to provide a controlled, repeatable emulation environment for the research, development, and evaluation of networking and information assurance algorithms for tactical wireless networks.

The System-of-Systems Survivability Simulation (S4), developed by ARL's Survivability/Lethality Analysis Directorate (SLAD), allows analysts to assess how threat effects, such as ballistics, computer network operations, and electronic warfare, impact a small-scale force in a mission context.

This Director's Strategic Initiative (DSI), a collaborative research effort between CISD and SLAD to interoperate the WEL and S4, enhances the analysis ability of both directorates. The WEL enhances the communications realism of the S4 suite and supports increased fidelity in the modeling of communications effects. The S4 enhances the domain fidelity with an embedded military domain–driven decision-making environment to better measure network technology interactions between Soldiers and equipment. Success will significantly improve the Army's ability to conduct SoSA and assess the impact of new equipment and technology on Soldiers and warfighters in a mission context.

**15. SUBJECT TERMS**

S4, WEL, DSI, network, MANET, mission, survivability, vulnerability, SLVA

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# 1. Introduction/Objective

## 1.1 Background

The Department of Defense (DoD) aims to provide warfighters with an end-to-end, seamless network-centric enterprise communications network. Evaluating the achievable performance of such a network in operational environments is essential to guiding requirements, design, and procurement activities. However, the DoD currently lacks the capability to analyze the complex networked interactions between warfighters and equipment in that operational environment. The U.S. Army Research Laboratory (ARL) has made significant investments developing a variety of modeling and analysis capabilities to analyze the impact of technology solutions on warfighters. Yet, there is no effective means to link high-fidelity communication modeling with System-of-Systems Analysis (SoSA) tools to provide a mission-based performance analysis tool set for evaluating this end-to-end enterprise infrastructure.

ARL's Computational and Information Sciences Directorate (CISD) has developed the Wireless Emulation Laboratory (WEL). The WEL provides a controlled, repeatable emulation environment for the research, development, and evaluation of networking and information assurance algorithms for tactical wireless networks. ARL currently uses the WEL to conduct basic and applied research in wireless networking and security.

ARL's Survivability/Lethality Analysis Directorate (SLAD) has developed the System-of-Systems Survivability Simulation (S4). S4 is a simulation engine and a set of software tools that allow analysts to assess how threat effects, such as ballistics, computer network operations (CNO), and electronic warfare, impact a small-scale force in a mission context. ARL currently uses S4 to conduct SoSA of battalion or smaller-sized forces.

## 1.2 Objective

At the corporate level, the long-term goal of this Director's Strategic Initiative (DSI) research effort is to develop an interoperable suite of tools that support SoSA regarding the impact of network technology on mission performance.  However, the intent of this DSI is not to create a robust set of tools but to assess the feasibility of integrating two existing tools and accomplishing some level of integration. If this DSI succeeds, it will provide a seed capability for the long-term corporate goal.

At the directorate level, CISD's objective is to improve the modeling of military decision making in the WEL and to increase the realism of the military scenarios used in WEL emulations. SLAD's objective is to increase the fidelity of its communication modeling in S4 by adding engineering-level Mobile Ad hoc Network (MANET) emulation capabilities, thereby enhancing the fidelity of its system-of-systems analysis activities.

# 2. Approach

## 2.1 The System-of-Systems Survivability Simulation (S4)

SLAD's mission is to provide survivability, lethality, and vulnerability analyses (SLVA) and expert consultation to its customers. Important customers include the Army's independent evaluator the Army Test and Evaluation Command, program managers, and Army decision makers. Traditionally, this activity focused on single-thread analyses; such analyses characterize the interaction between a single item of equipment and one or more threats, as if that interaction took place in isolation from all else. Although the SLVA of individual items remains important, it is no longer sufficient to address the technical and business concerns of many SLAD customers. The newer concerns are inherently at the SoSA level. Army and defense leadership is intent on fielding a network-enabled force and acquiring complex packages of military capabilities that will support the full range of Force Operating Capabilities (*1*). A comprehensive analysis of these packages requires us to portray the results from subtle engineering interactions among different systems in the capability packages. We must consider the whole system of systems (*2*).

SLAD is using and further developing S4 (*3*) to approach these broader survivability issues (*4*). Because S4 provides the ability to analyze capability packages in a mission context, SLAD analysts are no longer limited to tools that work only for single-threat analysis. We use S4 to illuminate higher-level complexities and interactions in the context of explicit operational missions. By assessing survivability issues in the context of relevant operational missions, analysts can now provide metrics that address broader and more subtle analytical questions that have been beyond the reach of single-threat analysis. The results are also more relevant to the warfighter because we develop them in an operational rather than a merely technical context.

S4 is a constructive simulation and a set of software tools. At its core, S4 is a Java implementation of an agent-based modeling paradigm (e.g., see Wooldridge [*5*, *6*]); however, unlike other agent-based models, in S4 each agent carries with it explicit representations of the military or tactical decision-making processes carried out by battalion, company, or platoon leaders in the future force. While the original impetus for S4 was the study of information flow and tactical decision making, as the need arises, S4 incorporates models of particular effects from subject matter experts in areas of ballistics, CNO, electronic warfare, mobility, etc. Each agent in S4 must respond to information about itself, its superiors, peers, and subordinates, as well as its adversaries in a manner consistent with the military decision-making process and Army doctrine. However, threat effects, such as ballistic events, electronic warfare attacks, and CNO, can perturb information flow and thus agent decisions. Consequently, with S4, analysts can assess the system-of-systems impact that these perturbations—for example, a loss of a road wheel or the presence of a threat jammer—will have on current and future force mission execution. To support these assessments, S4 has developed a comprehensive set of user interface–based analytical tools, methodologies, and software interfaces to capture warfighter knowledge in an easy and domain-relevant manner.

## 2.2 The Wireless Emulation Laboratory

The WEL at ARL was developed so that researchers could evaluate the actual software being used at the network layer and above. The WEL was fashioned to produce a controlled, repeatable experimentation environment for the research, development, and evaluation of communication and security algorithms for tactical wireless mobile ad-hoc networks. We use emulation as a means to efficiently and realistically study MANET as opposed to simulation and experimentation. Emulation provides a middle ground between the two; whereas the systems and applications are real, only the lower layers, Media Access Control/Physical (MAC/PHY), of the network stack are simulated.

The WEL originated as several laptops connected together in the emulation environment using a suite of tools originally developed by the Naval Research Laboratory called Mobile Ad-hoc Network Emulator. This suite of tools allowed for only homogeneous types of networks to be modeled and was limited in its ability to fully model the MAC and PHY layers. Currently in the WEL, the study of MANET is realized by conducting and analyzing real-time emulation experiments driven by the Extensible Mobile Ad-hoc Network Emulator (EMANE) and a suite of software tools used for experiment/scenario design, visualization, and analysis. EMANE allows for the creation of heterogeneous network emulation by using a pluggable MAC and PHY layer architecture. EMANE bases this pluggable architecture on the use of Extensible Markup Language (XML) to decouple the network emulation software components. The EMANE software is based on three main components (modules): the Network Emulation Module (NEM), Transport Module, and Event Module. A depiction of the models is given in figure 1.

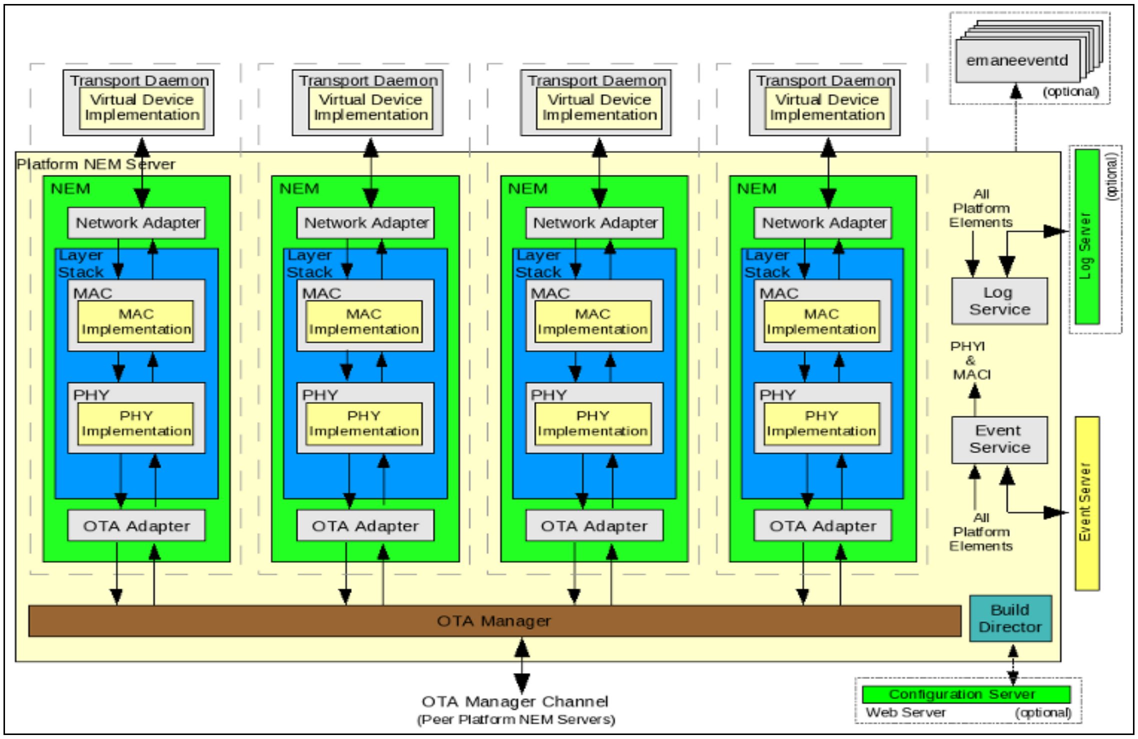


Figure 1. EMANE platform server hosting four NEMs.

The NEM is the heart of EMANE's emulation ability. It listens to "over-the-air" (OTA) packets that are transmitted in the emulation environment by connecting to a multicast channel. A NEM encapsulates all of the MAC and PHY layer implementation for a defined radio type. Currently, the following three different MAC implementations are implemented within the EMANE suite of tools: RF_pipe, 802.11a/b/g, and Soldier Radio Waveform (SRW). Each model utilizes the universal PHY layer implementation.

The RF_pipe's MAC model is a generic radio model that provides simple jitter and delay effects and the ability to enable and disable listening in promiscuous mode. In promiscuous mode, all OTA packets are sent up from the PHY layer to the network layer. If promiscuous mode is not enabled, only multicast/broadcast and unicast packets bound for that local node are sent up to the network layer. The 802.11a/b/g model emulates the IEEE 802.11 MAC layer's distributed coordination function channel access scheme on top of the IEEE 802.11 direct spread spectrum sequence and orthogonal frequency division multiplexing signals in space. The 802.11 a/b/g model has an additional feature that can incorporate flow control when used with the EMANE Virtual Transport. Flow control provides a mechanism to adjust the modulation scheme used to conform to the IEEE 802.11 standard. The third model that is incorporated into the WEL is the SRW model. This model is based on early implementations of the Joint Tactical Radio System (JTRS) tactical military communications waveform designed to network radios on the battlefield.

The Transport Module creates and manages the connection to each respective NEM and serves as the entry/exit point of the NEM stack. This connection is the bridge linking the node to the

NEM that is responsible for the transmission of packets across the emulation environment. When an application sends out a packet, it is pushed through the NEM stack using the transport module where it is placed on the OTA channel to emulate a transmitted packet. Likewise, when a node receives a packet, it is picked up off of the OTA channel and processed by the PHY and MAC layer to determine if the packet should be passed up to the transport module. If the packet is pushed up the NEM stack to the transport module, it is injected into the kernel IP stack and used by the corresponding application.

The Event Module is the general framework that provides for the creation and management of generators and agents of events. This framework resembles a classic client/server method, where the agents register to receive events from the generators that correspond to the given NEM. An example of this exists in the way that the NEM is updated with position or path-loss information. The interval in which events can be transmitted may vary, but in general events occur every second. When the agent receives the event, it passes the event to any application that is listening on the NEM for an event-driven process. One of the most common examples of this is the use of a global positioning system (GPS). The event generator sends out the GPS coordinates of each of the NEMs, and each NEM listens for its respective GPS coordinates and uses that information to determine connectivity within the given scenario.

### 2.3 Approach

Our approach consists of three phases. Each phase seeks to build upon the knowledge gained in the previous step to enable additional increasing interoperability between the two tool suites. Figure 2 shows the process of adding interoperability between the tool sets.

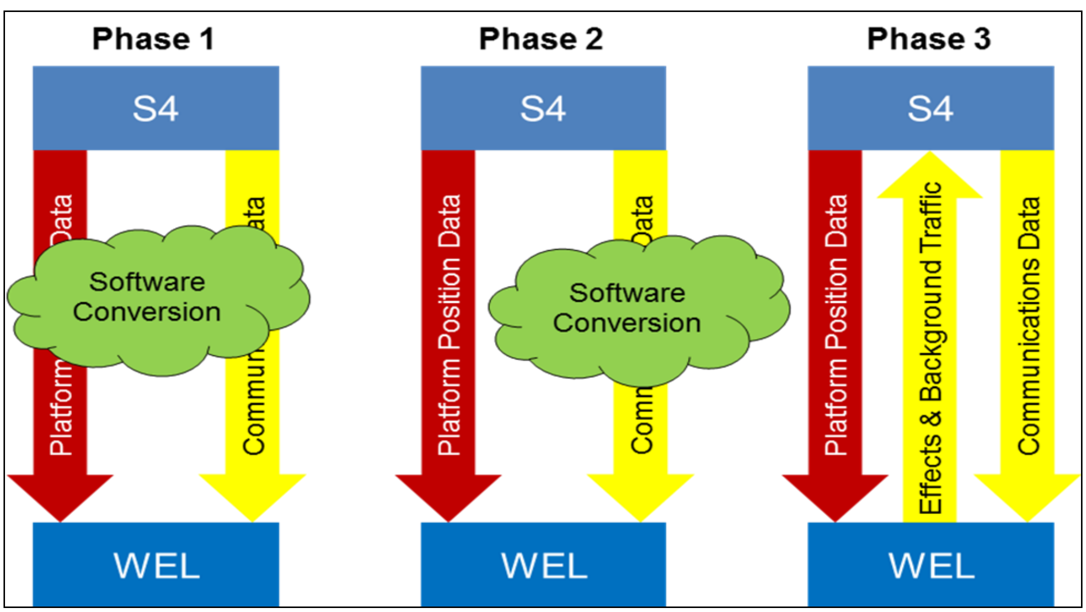


Figure 2. Three-phase approach to interoperability.

### 2.3.1 Phase 1 Effort

The primary objective of phase 1 is determining what interoperation means in the context of the S4 and the WEL as well as identifying the required resources. In phase 1, we will exchange tools and demonstrate the use of S4 outputs as inputs to the WEL. We will limit interoperation to sequentially using the scenario and output files/results from one tool as an input to the other tool.

In particular, we will examine the technical challenges (table 1) and develop techniques that will overcome these challenges or identify the limits of achievable interoperability. At a high level, S4 runs as a single-threaded application with all of the decision-making processes running on a single machine. In contrast, the WEL runs in a distributed manner, with each user/radio running on a separate machine (actual hardware or virtual machine). Therefore, techniques to link the centralized decision-making processes within S4 with the distributed processes in the WEL need to be developed. In addition, the team must address the issue of time management before the tools can interoperate. S4 is a constructive simulation with discrete time steps (0.5 s) for decision-making reasoning, and depending on the level of decision-making actions being computed, it may run faster or slower than real time. The WEL, in contrast, is continually time based for real-time protocol operation.

Table 1. Chief technical challenges to interoperability.

| Technical Challenges | S4 | WEL |
|---|---|---|
| Structure | Centralized, single-threaded constructive simulation | Distributed, multithreaded, emulation |
| Execution | May be faster or slower than real time | Real time |
| Simulation time | Discrete | Continuous |
| Repeatability | Repeatable for a given random number seed | Not necessarily deterministic because nodes run applications and protocols |
| Message content | Only traffic of interest is modeled, and content has meaning | Bits and bytes modeled but content often abstracted |
| Entity state | Can be altered by many means—ballistics, electronic warfare, CNO, etc. | Primarily network state |

In addition, it is important to note that S4 is deterministic for a given random-number seed. WEL is not necessarily deterministic (nodes run applications/protocols). The impact on this difference on SoSA will need careful consideration. Of lesser concern but still important are issues associated with managing and exchanging entity state information between the tools and managing message content.

### 2.3.2 Phase 2 Effort

In phase 1, the team identified possible approaches to overcoming the technical barriers associated with interoperation. In phase 2, the team will apply this knowledge to create a partial link between S4 and the WEL. Overall, the level of interoperation will be sequential; however, at the completion of phase 2, platform position data from S4 will dynamically drive the network node locations in the WEL. The WEL will still pass communications data that underwent a software conversion process prior to operation. This enables the team to demonstrate S4 driving mobility in the WEL at runtime while at the same time allowing the team time to identify approaches to the far more complex problem of handling communications between S4 and the WEL in real time.

We will develop common data exchange tools to support using scenario data and experimental results from the different tools. We will also identify and document methods for solving more "complex" dynamic interactions, such as exchanging entity-state data and sharing communication events at run time.

### 2.3.3 Phase 3 and Beyond Effort

In phase 3, and based upon our experiences with phase 2 interoperation, the team will adapt our shared toolbox to support more effective analysis of system of systems. We will extend interoperation to more complex dynamic interactions between WEL and S4, and enhance the realism and accuracy of our joint analysis capability.

## 3. Results

### 3.1 Chronology of Key Events

While this DSI received its initial funding in April 2011, in two occasions the team presented its proposal to external audiences as an initial peer review. In January 2011, the audience was a select group of the National Research Council (NRC) Technical Advisory Board (TAB) referred to as the mini-TAB. ARL convened the mini-TAB to focus on specific issues related to SLAD's SoSA program. The proposal received favorable reviews to the extent that the team determined that we were on a technically sound approach. In April 2011, the team presented the proposal to the NRC Cross-Cutting TAB, with similar results. In August 2011, the team presented the proposal to the full NRC TAB at the review of SLAD's program. At this review, the TAB panel members again gave a positive review of the efforts to date and suggested several possible uses for the S4\WEL when we attained full interoperability. In all these cases, the TAB panelist agreed with the assertion that the functionality intended for this DSI targeted the right problems.

### 3.2 Phase 1 Progress

The WEL/S4 integration is based upon a three-phase approach where in the first phase, outputs from S4 are to be implemented in the WEL. The initial outputs that are being implemented are the mobility and communication behaviors of the nodes in the S4 simulation. The mobility is needed to feed GPS coordinates into EMANE in order to generate the events needed to determine connectivity. During this first phase, ARL CISD began to understand how the S4 software was implemented, where its output files were located, and what those files represented. Based off of trial runs of the S4 software, it was determined that the file “platform_moves.csv” contained the GPS coordinates (in terms of meters) of each node used in the simulation. In order for this to be understood by EMANE’s event generator, this file needed to be read and converted into an XML file of corresponding node’s latitudinal and longitudinal coordinates. This was accomplished by using information in the “TerrainMetadata.txt” file, which gave the latitude and longitude coordinates (in meters) of the lower-left position of the map used in the S4 simulation. Once this information about the map used in the S4 scenario is determined, the GPS coordinates can be calculated using the function in the appendix.

The output that is being implemented within this phase is the communication behavior. This relates to the flow of information within the S4 simulation. Certain nodes send information at particular times during the simulation, and those interactions need to be reflected in the emulation environment. As an initial implementation, we are using the 802.11a/b/g radio model to determine network connectivity. This is different from what S4 is using as a radio model, but the intent is to recreate the flow of information through the network while developing a model that reflects the radios being used in S4. The flow of information initially will be done using a toll called Real-Time Application Representative (RAPR). This tool uses message generation software that sends and responds to data traffic patterns. If the traffic patterns in S4 can be determined from its output, then RAPR can be used to model that flow between the nodes. The work in this portion of phase 1 is still ongoing.

## 4. Conclusions

### 4.1 Transitions

As currently envisioned, and given the inherent complexity in the integration, we expect this DSI to transition to internal customers in the form of SLAD and CISD. Among the interests expressed, SLAD expects to use the interoperation of the WEL and S4 to “tune” its Brigade and Below, Propagation and Protocol (B2P2) model. B2P2 is the existing communication model in S4 that allows the passing of messages between agents; however, it is a simulation of what the WEL emulates and as such will never have the fidelity of the WEL. In using the S4/WEL to tune B2P2, SLAD expects a more realistic representation of network effects (latencies, losses, etc.) when it runs S4 constructively in its SoSA activities. In the long term, SLAD expects to use its SoSA capabilities to assess the survivability gains and the vulnerability impacts of developmental radio and networking technologies such as JTRS and the Warfighter's Information Network-Tactical (WIN-T). Ideally, the intent is to identify survivability gains from the networks to "self-form," "adapt," and "heal." Additionally, SLAD will use its SoSA capabilities to determine if these self-forming and adaptive networks introduce vulnerabilities and, if so, evaluate the mitigations we can deploy and assess their impacts.

From CISD's perspective, the internal transition of this project would enhance the ability to evaluate other ongoing research efforts for mission effectiveness. In particular, the research being performed in the Quality of Information project would be able to leverage this tool to determine a level of effectiveness when certain weights are placed on the information passed throughout the network. The effects of placing importance on some data over others can be determined when used in a scenario that requires mission urgency. This tool provides a platform for evaluating how effective and efficient the "quality" placed on information becomes in obtaining the mission objective. The same is evident in the research being performed on distributed dynamic federated databases. CISD is researching Gaian Databases to distributively store information that can be dynamically retrieved. This information can come from many different sources and can be used by any subscriber to the stream of information. This tool can determine whether this database system is effective in accomplishing the mission. Additionally, the tool provides an electronic warfare capability that is not present in the WEL. The transition of this capability will help to enhance the development of effective tools and protocols used in a MANET environment.

## 4.2 Future Research

Since this DSI has only been active for approximately 6 months, it is perhaps premature to plan follow-on research efforts. However, there are several near-term obstacles that we will need to address to accomplish this DSI. These research areas target several of the key barriers identified in Table —namely, the ability to manage simulation time, repeatability, closed loop communications, and entity state. Our expectations at this point are that these target areas are in decreasing priority. Since S4 is a constructive simulation, and the WEL is at its core an emulator, developing an approach to simulation time management is essential to creating an interoperable simulation. We expect to tackle this effort first; however, we do not expect a workable solution until year 2 to early year 3 in the DSI. A second major effort is to ensure that once we join S4 and the WEL, we can interoperate them in a repeatable manner, and by repeatable we mean that the simulation outputs are identical for a given random number seed. Our intent here is to ensure that we are able to reproduce results as needed to support the analysis mission of SLAD and the algorithm development mission of CISD. Here we also do not expect results until year 2 or 3 of the DSI. Finally, the two remaining thrust areas, that of closed loop communications and the exchange of entity states, we expect to address in the course of addressing our first two priorities; that is, we expect to identify approaches to manage these requirements late in the first year of execution or in the second year of this DSI.

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# Appendix. Phase 1 Python Conversion Scripts

Python code to convert meters to latitude and longitude:

```
##############################################################################
###########
   #  __meters2GPS
   #
   # parameters: lat_n_meters, lon_n_meters
   #
   # description:
   #     This routine will change the meter value of the lat, lon, alt format
   #     of the coordinates into the GPS (lat, lon, alt) format needed for
   #     EMANE.

##############################################################################
###########

   def compute_lat_lon(self, lat_n_meters, lon_n_meters):

       R = 6367*1000    # Circumference of the earth @ equator

       # LL_LAT comes from terrainFile
       # This is equation to find latitude

       latitude = ((float(lat_n_meters) * 180)/(R * math.pi))+ self.LL_LAT

       # This is equation to find longitude
       # LL_LON comes from terrainFile

       longitude = ((float(lon_n_meters) *180)/(R* math.pi *
            math.cos(self.LL_LAT)))+ self.LL_LON

       return latitude, longitude
```

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## List of Symbols, Abbreviations, and Acronyms

| | |
|---|---|
| ARL | U.S. Army Research Laboratory |
| B2P2 | Brigade and Below, Propagation and Protocol |
| CISD | Computational and Information Sciences Directorate |
| CNO | Computer Network Operation |
| DOD | Department of Defense |
| DSI | Director's Strategic Initiative |
| EMANE | Extensible Mobile Ad-hoc Network Emulator |
| GPS | global positioning system |
| IEEE | Institute of Electrical and Electronics Engineers |
| IP | Internet protocol |
| JTRS | Joint Tactical Radio System |
| MAC | Media Access Control |
| MANET | Mobile Ad-hoc Network |
| NEM | Network Emulation Module |
| NRC | National Research Council |
| OTA | over the air |
| PHY | Physical |
| RAPR | Real-Time Application Representative |
| S4 | System-of-Systems Survivability Simulation |
| SLAD | Survivability/Lethality Analysis Directorate |
| SLVA | survivability, lethality, and vulnerability analyses |
| SoSA | System-of-Systems Analysis |
| SRW | Soldier Radio Waveform |
| TAB | Technical Advisory Board |
| WEL | Wireless Emulation Laboratory |

| | |
|---|---|
| WIN-T | Warfighters Information Network – Tactical |
| XML | Extensible Markup Language |

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